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Loch Lomond (Younger Dryas) Stadial Glaciation Style at Wolf Crags, Eastern Lake District

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Abstract

Several studies have attempted to reconstruct Loch Lomond Stadial (12.9-11.7 cal. ka BP) glaciers in Britain. In the Lake District early interpretations of moraine ridges led to the reconstruction of predominantly cirque and valley glaciers. However, more recent reinterpretations based on analyses of summit geomorphology and modern analogue glaciers, have argued that a plateau icefield was a more plausible landsystem for parts of the Lake District during the LLS. This study uses geomorphological mapping of landforms at and adjacent to Wolf Crags, the site of a previously reconstructed cirque glacier, at the northern end of the Helvellyn range, eastern Lake District. Evidence of blockfields, meltwater channels and gullies on the plateau edges are indicative of a cold-based protective ice mass on the summit. The reconstructed ice-marginal positions demonstrate retreat of two outlet glaciers at Wolf Crags and in the valley of Groove Beck towards a contiguous glacier on the plateau above these sites. It is suggested that a plateau icefield is a more plausible glacial landsystem for the Wolf Crags region and probably fed other outlet glaciers in the valleys to the south of Groove Beck. This highlights the need for a reassessment of previous palaeoclimatic inferences made for the Lake District during the Loch Lomond Stadial.

Introduction

The Loch Lomond Stadial (LLS; 12.9-11.7 cal. ka BP) was the last episode of glaciation in Great Britain and led to glacial readvance following ice retreat at the end of the Last Glacial Maximum (LGM; ~27-26 cal. ka BP) (McDougall, 2013). In the Lake District, Manley (1959) and Sissons (1980) extrapolated LLS ice margins based on moraine configuration, assuming ice-free summits. Sissons (1980) reconstructed 64 cirque and valley glaciers associated with the LLS in the Lake District. Due to the small size and isolated nature of the glaciers, it was believed that the Lake District was marginal for glaciation and must have received low levels of precipitation (Sissons, 1980; McDougall, 1998). However, more recent studies have mapped lateral, terminal and recessional moraine ridges with implications of more extensive ice cover, including plateau icefields in the Central Fells (McDougall, 2001; Wilson, 2002, 2004). It is argued that the failure of Manley (1959) and Sissons (1980) to recognise former icefields is a reflection of the use of 'moraine freshness' to identify LLS moraines, and a limited understanding of the glaciological significance of plateau icefields in supplying ice to the surrounding valleys (McDougall, 2013).

A more comprehensive approach to determine glaciation style is using glacial landsystem models. This is a more thorough approach to reconstruction than moraine ridge mapping alone, by assessing the geomorphology and the combination of landform units in order to determine the style of glaciation (Evans, 2005; Bickerdike et al., 2017.). Five glacial landsystems were identified by Bickerdike et al. (2017) as possible styles of glaciation in the UK during the LLS, with four applying to the Lake District. The first and largest of the landsystems are ice caps, characterised by landforms discordant with the underlying topography, and a palimpsest landscape of flow directional landforms formed by migrating ice divides (Benn and Evans, 2010; Bickerdike et al., 2017). Second are plateau icefields, composed of cold-based ice on the summits with limited depositional processes on the plateau, preserved relict blockfields, and plateau periphery landforms (Rea et al., 1998; McDougall, 2001, 2013; Boston et al., 2015). Third are valley glaciers which are constrained by topography and produce depositional landforms on the valley floor transitioning to periglacial landforms at higher elevations (Benn and Evans, 2010; Bickerdike et al., 2017). Fourth are cirque glaciers which are topographically constrained by a steep back wall and frequently produce nested terminal and recessional moraine sequences; they are typically surrounded by periglacial landforms such as solifluction features (Bickerdike et al., 2017). In this paper a landsystems approach is used to determine the style of glaciation at Wolf Crags, the site of a previously reconstructed cirque glacier, and in the adjacent valley of Groove Beck, a site not previously recognised as having held a LLS glacier.

Study Area

The study area is focussed on Wolf Crags (NY 356222), a north-facing cirque adjacent to the

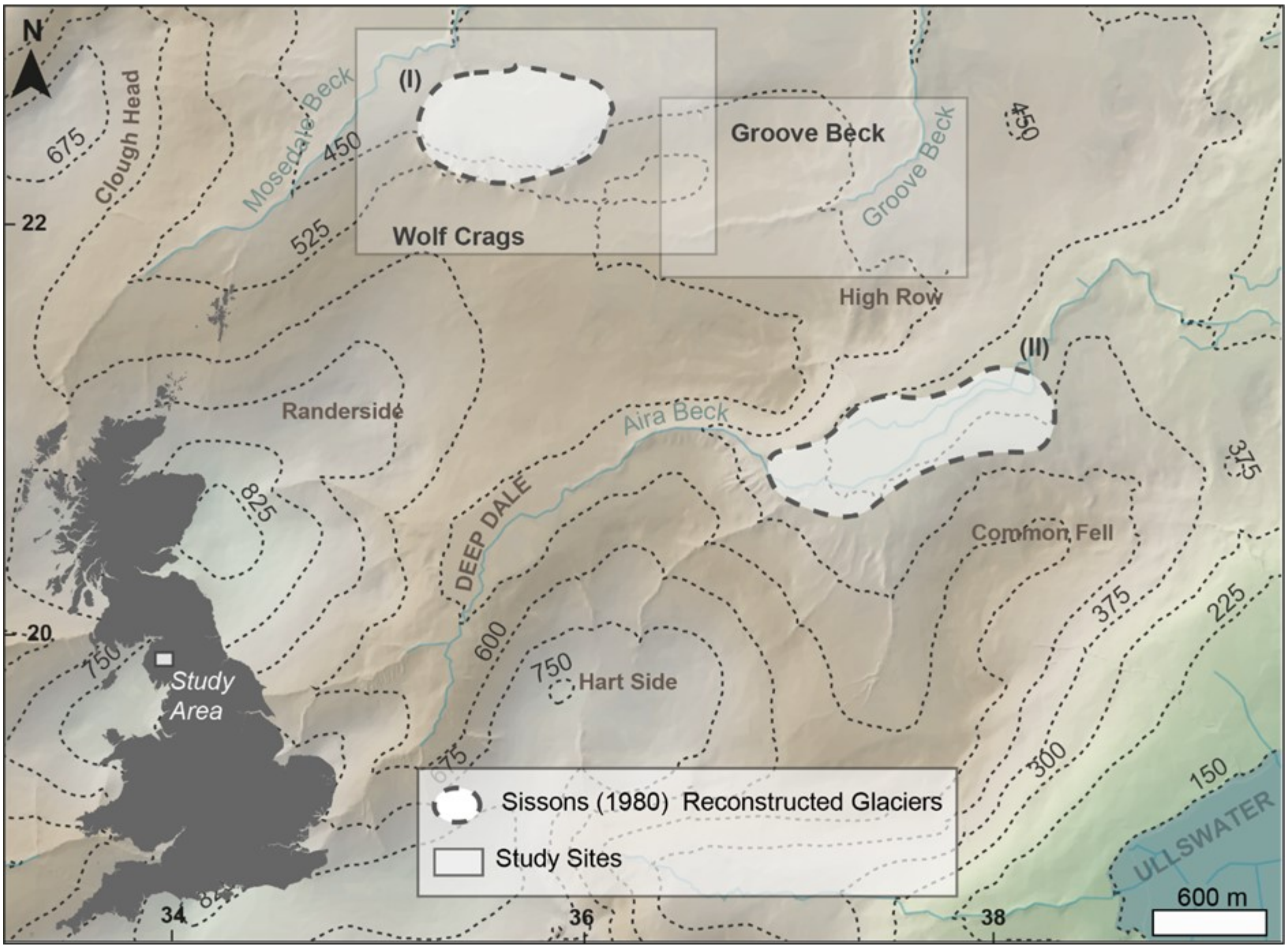

Figure 1. The two locations (Wolf Crags and Groove Beck) in the Eastern Lake District chosen for detailed field mapping. (1) A cirque glacier was previously reconstructed at Wolf Crags and (11) A valley glacier in Deepdale by Sissons (1980). Grid coordinates OS NY square. Ordnance Survey data © Crown copyright and database rights 2017.

valley of Groove Beck (NY 373221) to the east, at the northern end of the Helvellyn range in the Eastern Fells of the Lake District (Fig.1). Manley (1959) and Sissons (1980) concluded that a small isolated cirque glacier nourished by wind-blown snow from the adjacent plateau existed at Wolf Crags, however, neither of these researchers recognised depositional glacial landforms in the valley of Groove Beck to the east. Up to now, no studies have been conducted at Groove Beck to identify landforms associated with the LLS. Previous work has been limited to identifying a single drumlin on the top of the fell between Groove Beck and Deepdale, associated with the British-Irish Ice Sheet glaciation (e.g. Clark et al., 2012; Livingstone et al., 2008). No formal field survey has been undertaken at Wolf Crags since Sissons (1980).

Methods

Preliminary geomorphological mapping was conducted using satellite imagery. Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs) of 1:10,000 scale were used to create slope and hillshade models alongside Light Detection and Ranging (LiDAR) data, a remote sensing dataset to provide information on the topography of the study area. Field visits to Wolf Crags and Groove Beck (Fig.1) were undertaken to record glacial, periglacial, and more recently formed features. Ordnance Survey (OS) maps and a Global Positioning System (GPS Juno) were used to record key features and produce detailed field sketches which could then be transposed into a Geographical Information System (GIS) database. The field and imagery analysis data were then used to create the final geomorphological maps. Aerial data sourced from Getmapping and a 1:10,000 OS map was used as a backdrop to digitise the field evidence as they assisted with orientation of the landforms from the GPS coordinates, field sketches and photographs. The larger landforms and breaks in slope were digitised using the slope and hillshade

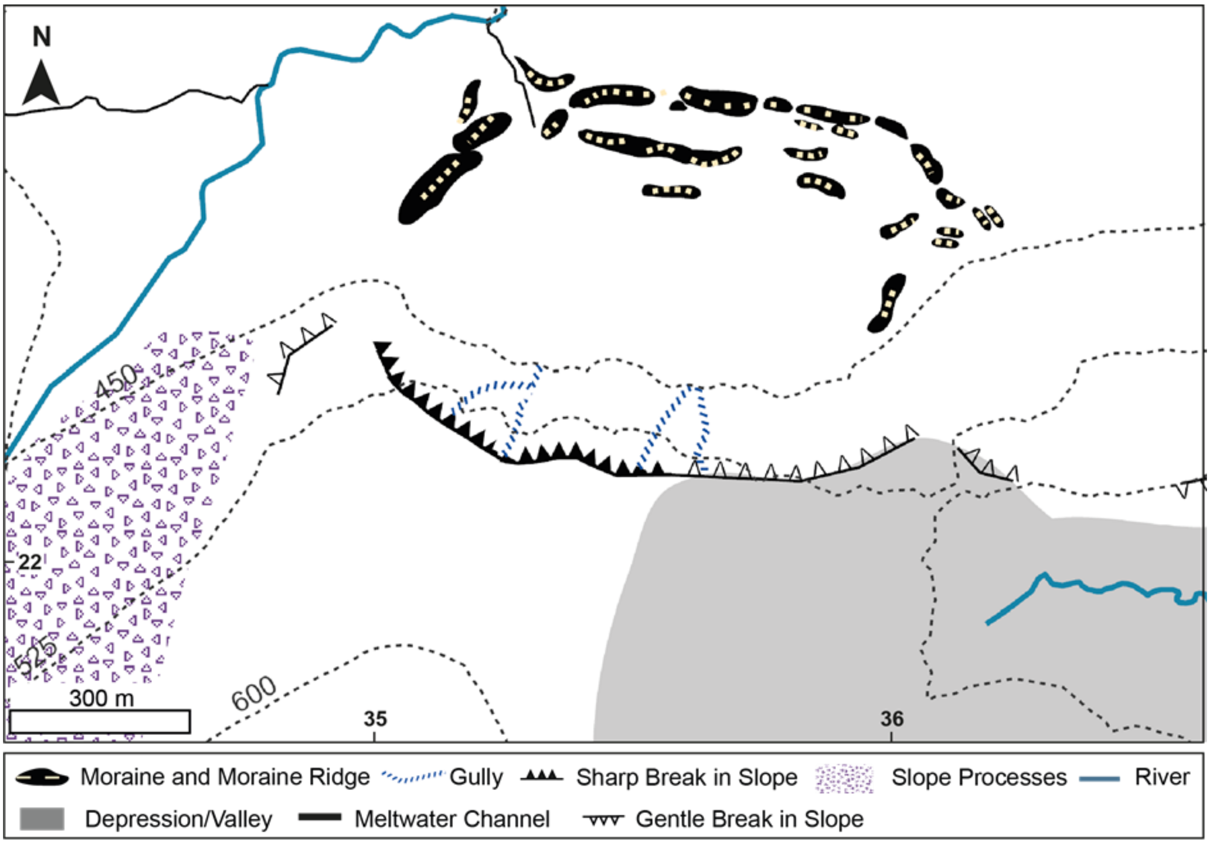

Figure 2. Geomorphological map of landform assemblages with particular focus on glacial landforms, based on field mapping and satellite imagery of Wolf Crags. Grid coordinates OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

models. This provided a single GIS database of features such as moraine ridges and mounds, meltwater channels and hummocky terrain. To determine the positions of the ice margins, a continuous line was used to join moraine ridges which form clear chains or linear sequences, following the methodology outlined in Bennett and Boulton (1993). These lines were then used to trace the retreat patterns of the glacier and aid in the determination of the ice source area (Bennett and Boulton, 1993).

Results

Glacial landforms are found at both Wolf Crags and Groove Beck through the field investigation, and larger structures were visible on the satellite imagery and DEMs in the surrounding area and on the adjacent summits.

Wolf Crags

The Wolf Crags landform was clearly identifiable by a sharp break in slope and craggy backwall on the edge of the plateau (Fig.2). North of the crag, a sequence of disconnected, lobate features interpreted as terminal moraines enclose the basin at Wolf Crags with fragmented retreat moraines towards the summit (Figs.2 and 3). The Wolf Crags basin is also bounded by a prominent lateral moraine on its western side (Figs.2 and 3). This contrasts with the eastern side where moraines present on the basin floor are orientated parallel to the break in slope with one smaller and less defined orientated perpendicular and extending down slope. Within the basin a small meltwater channel which feeds into Mosedale Beck breaches the lateral moraine on the west and the terminal moraines parallel to the crag (Fig.2). From the edge of the plateau, gullies extend down the face of the crag and a distinct depression on ththe easternmost edge of the summit continues downslope towards Groove Beck (Figs.2, 3, 4a and the easternmost edge of the summit continues downslope towards Groove Beck (Figs.2, 3, 4A and 4B). When viewed from the summit, this depression extends further onto the plateau to the south and east (Fig.2). From this depression the eastern side of the crag is of lower gradient and lacks the craggy backwall evident on the western side (Fig.2). The slopes on either side of Wolf Crags

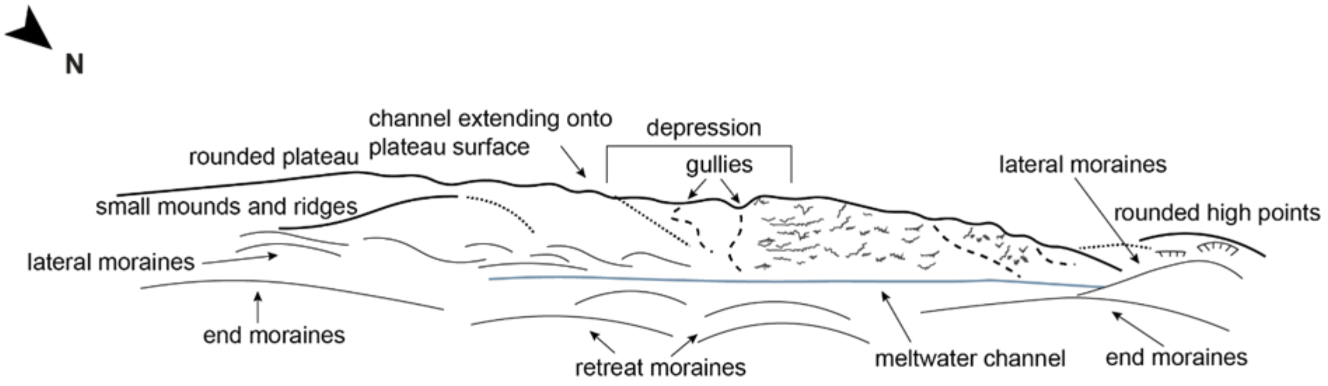

Figure 3. Annotated sketch from the north of the Wolf Crags landform (NY 356222) facing south. The Wolf Crags landform is the site of a previously reconstructed LLS cirque glacier. The sketch highlights the craggy back wall with moraine sequences flanking the rounded basin. Gullies can also be seen on the face of the slope descending from the plateau surface at the centre and the west of the backwall.

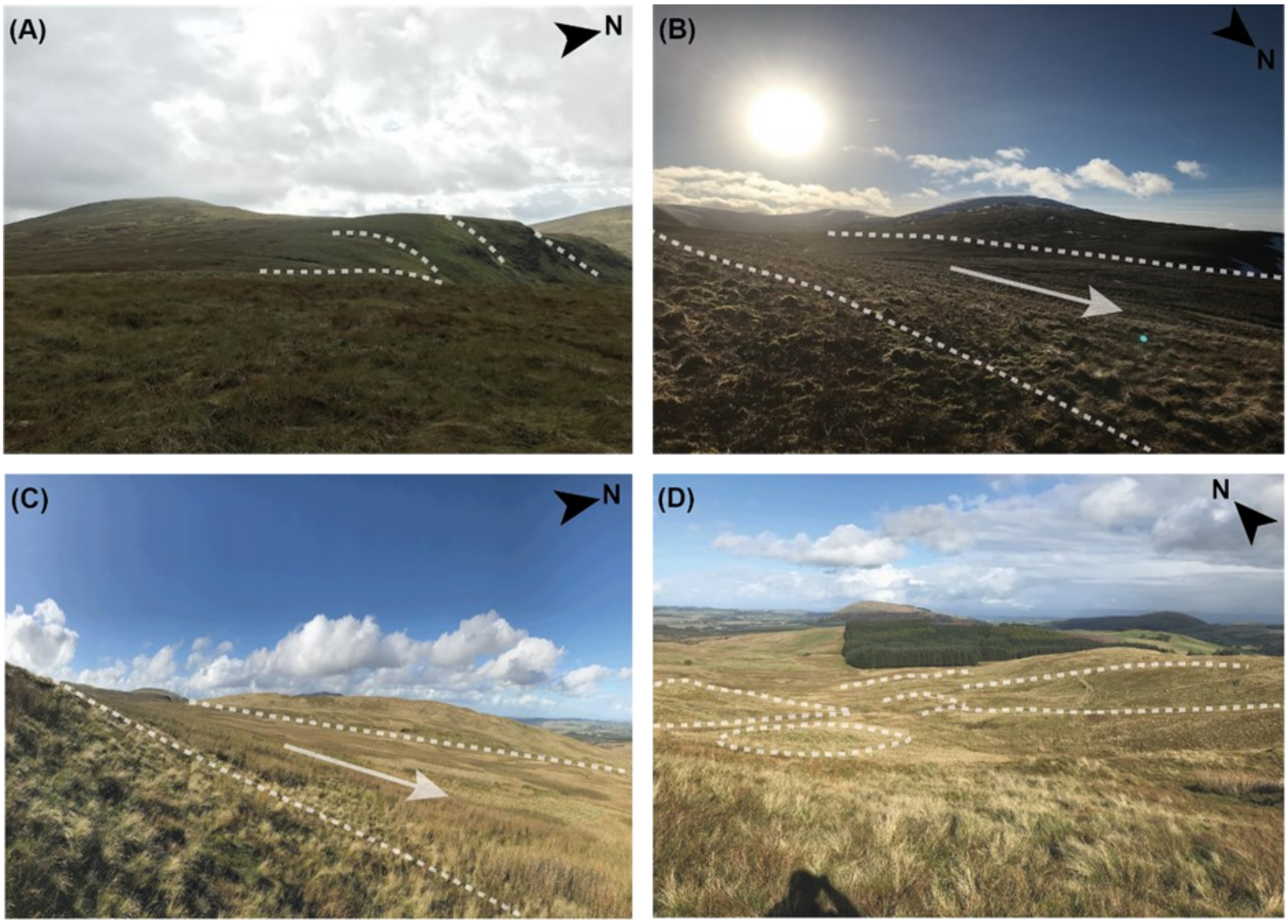

Figure 4. Photos of key features from Wolf Crags (A-B) and Groove Beck (C-D); (A) Gullies on the north facing slope of Wolf Crags (NY 356222) highlighted by the white dashed lines (B) Large depression on the plateau above Wolf Crags (NY 355218), highlighted by the white dashed lines. The arrow indicates direction of ice flow (C) Large depression in Groove Beck (NY 371219) (highlighted by the white dashed lines) that extends to the plateau above Wolf Crags large depression, The arrow indicates direction of ice flow (D) Moraines and hummocks outlined in dashed lines, trending down valley in Groove Beck (NY 373219).

are smooth and heavily vegetated with some evidence of former slope processes on the steeper western slope with large boulders and smaller rock fragments littering the ground.

Groove Beck

The Groove Beck site is east of Wolf Crags and hosts a topographic depression which extends back onto the plateau above the Wolf Crags landform (Fig.4C). The field survey revealed a distinct moraine sequence with lobate planforms trending from the valley floor towards the plateau surface above Wolf Crags in the west (Figs.4D, 5 and 6). The moraines are consistently well developed from the base of the depression towards the plateau surface. To the north of the river terrace there are also two large moraines and one medium sized moraine with long axes orientated upslope (Figs.5 and 6). Generally, the landforms to the north of Groove Beck are limited to higher ground. To the east of Groove Beck, the moraine sequences are poorly developed and there is extensive hummocky terrain where prominent moraine ridges are harder to identify (Fig.5). The hummocks, with erratics near their high points, are dissected by meltwater channels (Fig.6). Unlike Wolf Crags there is no evidence of periglacial processes at Groove Beck.

Summits and Adjacent Valleys

Satellite image analysis was performed across the wider study area including the plateau shown in Fig. 7. The slope and hillshade model highlighted the lack of sharp breaks in slope or any substantial relief between the plateau surface above Wolf Crags and Groove Beck (Fig.7). Further south, distinct and multiple valleys on the eastern slopes of the fells were identified (Fig.7). The northern most valleys are connected by meltwater channels which feed into the larger valley of Deepdale to the east (Fig.7). The southernmost valleys are often flanked by sharp breaks in slope, whereas in the north the breaks in slope are

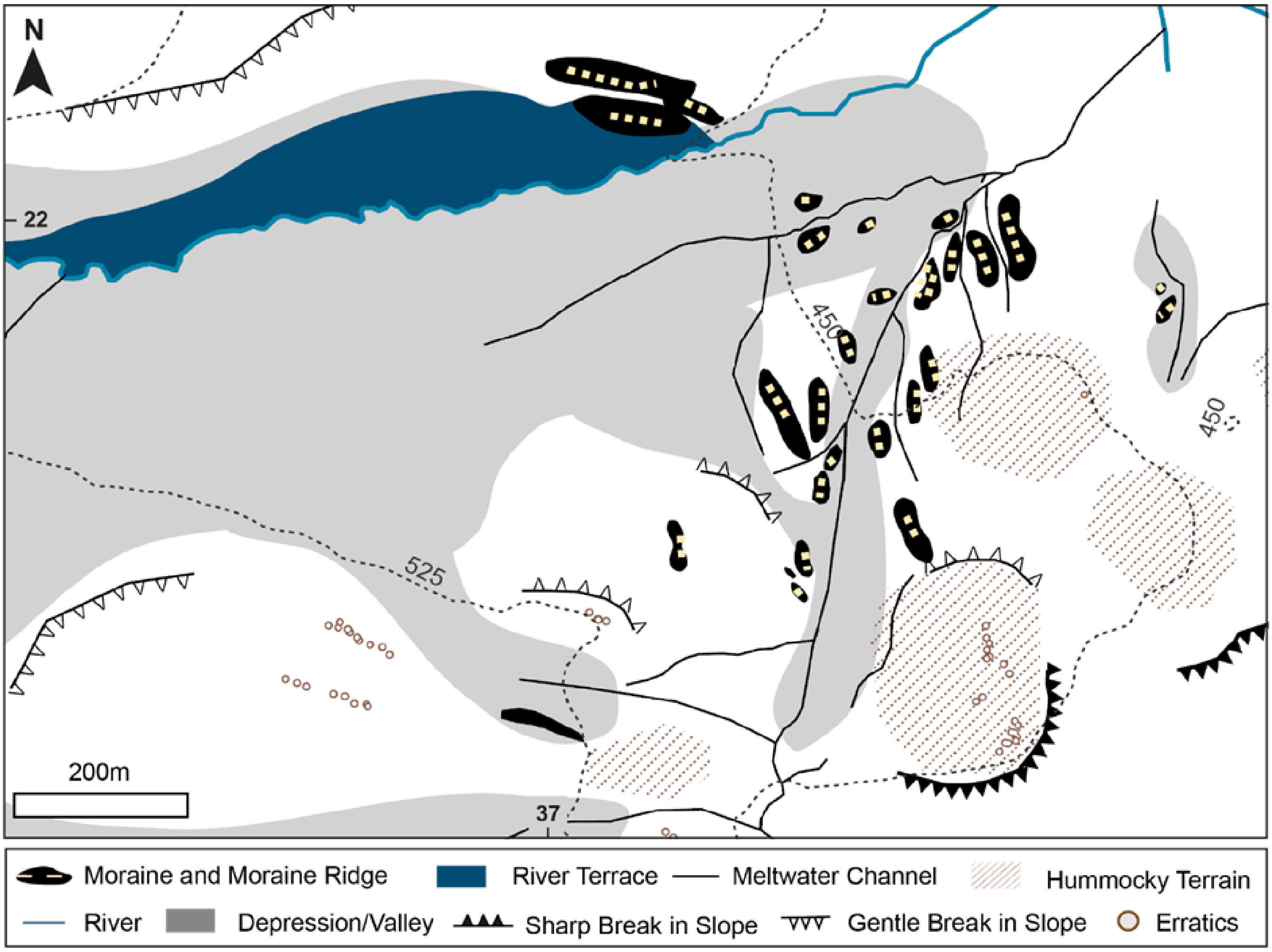

Figure 5. Geomorphological map of landform assemblages with particular focus on glacial landforms, based on field mapping and satellite imagery of Groove Beck. Grid coordinates OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

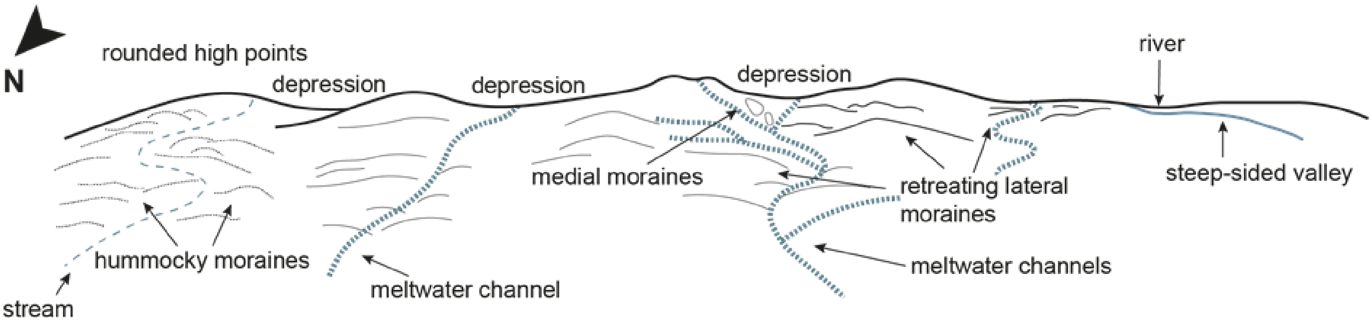

Figure 6. Annotated sketch of the landforms at Groove Beck (NY 373221). The Groove Beck site has not previously undergone any LLS glacier reconstruction. The sketch highlights the multiple depressions and well-defined moraine sequences in the western limits of the study site compared with the hummocky terrain in the east.

typically incomplete and slope more gently (Fig.7). Meltwater channels are found extensively within each valley with most either ending abruptly at the plateau edge or extending onto the plateau surface (Fig.7). Satellite imagery also revealed a number of blockfields on the plateau surface (Fig.7).

Reconstructed Ice Margins

The ice margins were reconstructed by joining the moraine crests from Wolf Crags and Groove Beck where prominent chains or linear sequences were identified. The terminal moraines encompassing the basin of Wolf Crags were used to delimit the margins of an outlet glacier showing a retreat pattern coinciding with the large depression on the eastern limits of the plateau –shown in Fig 2. The western margin of the Wolf Crags outlet glacier was delimited by the large lateral moraine and evidence of slope processes on the western slope of the Wolf Crags landform (Fig.8). At Groove Beck, the linear sequence and lobate outlines of the moraine ridges indicate their origins as recessional and of active ice retreat towards the higher elevation plateau. Fig.8 shows the maximum limits and retreat positions of the two outlet glaciers as they backwasted towards the plateau surface, suggesting that the ice within Wolf Crags and Groove Beck was contiguous. There is also a number of valleys on the eastern slope to the south of the Wolf Crags landform, including the nearby valley of Deep Dale, a previously reconstructed valley glacier (Sissons, 1980), that could have also potentially hosted an outlet glacier from the plateau icefield (Fig. 8).

Discussion

Evidence for a Plateau Icefield

Through an analysis of more recent reconstructions of Loch Lomond glaciers in the Lake District (e.g. Brown, 2009; McDougall, 1998; 2001; 2013), modern plateau icefield analogues, and the resulting work of Bickerdike et al. (2017), key plateau icefield signatures have been identified at Wolf Crags, Groove Beck and on the adjacent summits. In modern analogues in Scandinavia, the most prominent piece of evidence for the existence of plateau icefields is end moraines that extend from the valley floor towards the summit which remains almost featureless with little to no depositional evidence (Evans et al., 2002; Bickerdike et al., 2017). This is evident at Wolf Crags with end moraines that extend from the valley floor towards the plateau and in the clear back-wasting pattern of moraines in Groove Beck, out of the confines of the valley (Figs.2 and 5). These moraines display a linear sequence and lobate outlines, characteristic of actively retreating glaciers in upland areas (e.g. Bennett and Boulton, 1993; McDougall, 2001). Similar retreat patterns are seen in the valleys of outlet glaciers fed by plateau icefields in both the contemporary glacier settings of Arctic Canada and Norway as well as in the reconstructed glaciers in the Central Lake District (McDougall, 2001; 1998; Rea et al., 1998). The hummocky terrain to the east is also typical of a glacial environment within LLS limits, mainly associated with the topographic lows of plateau icefield landsystems compared to the well-developed often large distinct moraines found in glacial valley landsystems (Bickerdike et al., 2017).

It was previously considered that the Wolf Crags landform hosted a cirque glacier during the LLS; however, there is limited geomorphological

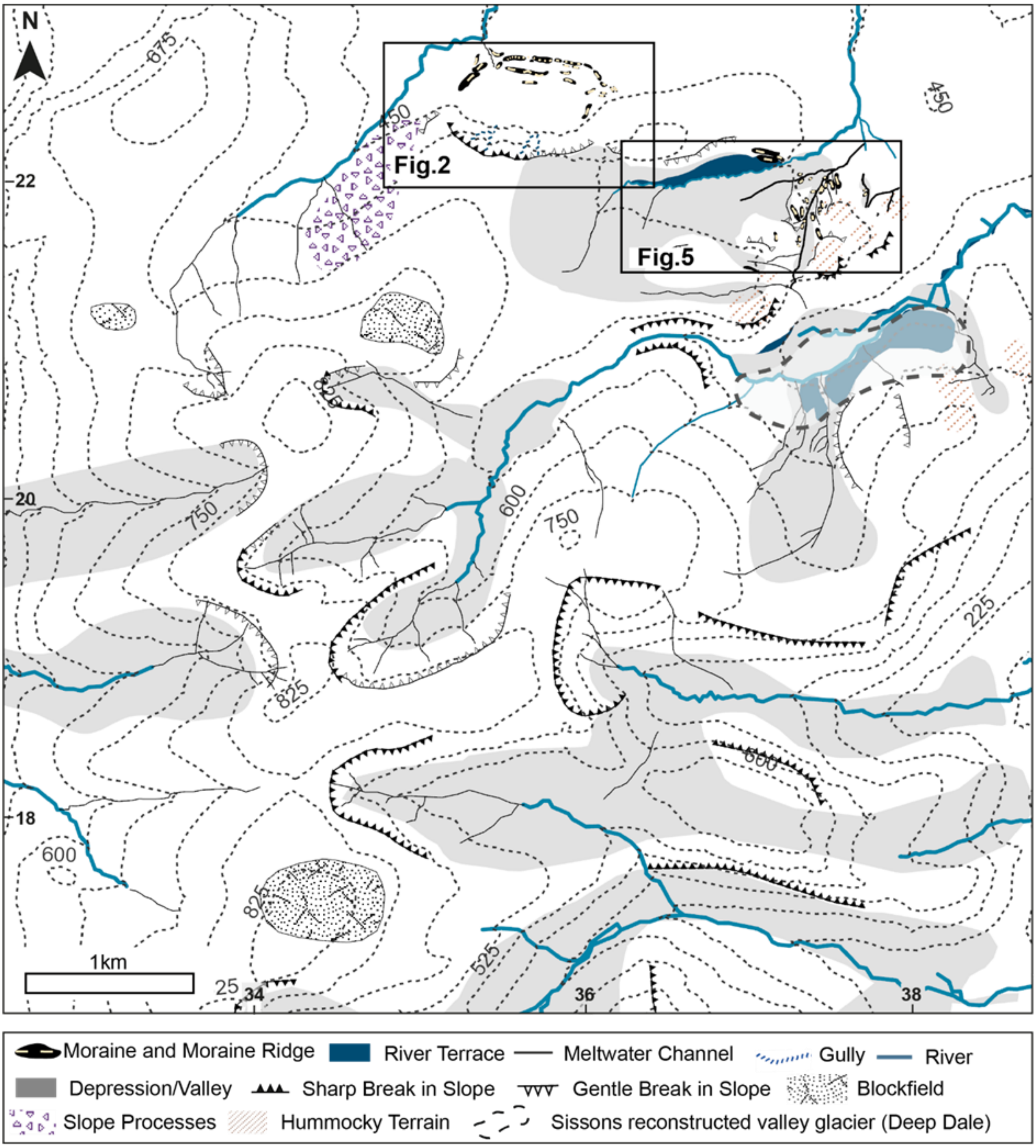

Figure 7. Geomorphological map of landform assemblages with particular focus on glacial landforms, based on field mapping and satellite imagery of Wolf Crags, Groove Beck and the plateau and the adjacent valleys. Sites of detailed field mapping, Wolf Crags and Groove Beck, are shown in the black boxes. Grid coordinates correspond to OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

evidence of cirque glaciation at Wolf Crags. The sparse evidence of periglacial processes on the western slope and limited evidence of periglacial processes elsewhere is not common for cirque glacial landsystems and contrasts with the thick talus slopes found on Ben More Coigach, northwest Scotland and LLS cirque glaciers in Wales (Bendle and Glasser, 2012; Chandler and Lukas, 2017).

Although it is possible the thick peat cover in the area is potentially masking periglacial evidence, the plateau periphery landforms and geomorphological evidence on the summit further supports the hypothesis of a plateau icefield. Gullies formed by draining meltwater and bed erosion at the edges of plateau were found extensively on the plateau edge above the Wolf

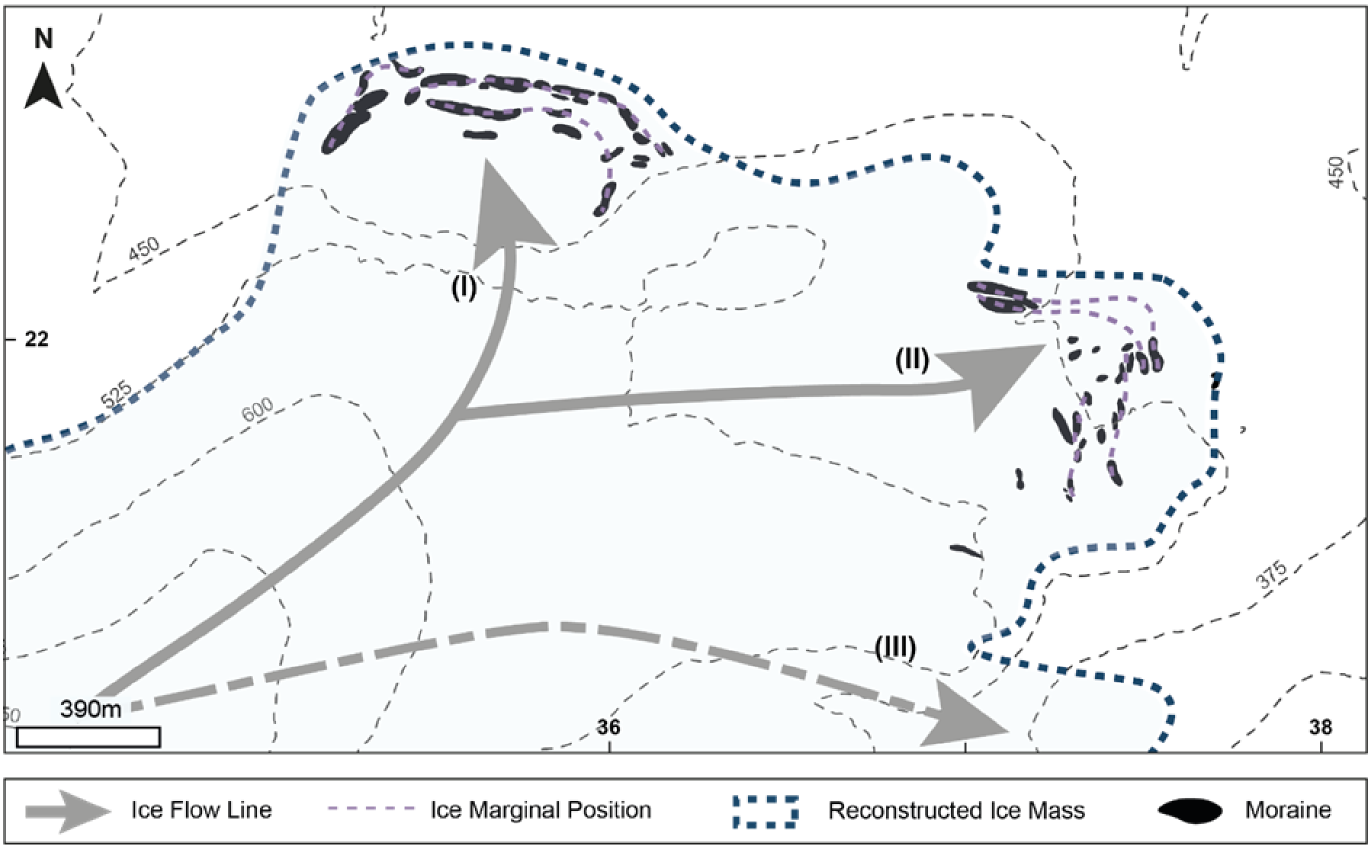

Figure 8. Interpretation of the ice-marginal positions from the landform assemblages of Wolf Crags and Groove Beck using extracted contour data at 35m intervals. Arrows illustrate the direction of ice flow originating from a plateau above (1) Wolf Crags, (11) Groove Beck and (111) an indicative flow line in Deepdale. Ice margins extending from the plateau surface indicate an origin from the same plateau icefield. Grid coordinates correspond to OS NY square. Content from Ordnance Survey data © Crown copyright and database rights 2017.

Crags landform indicating a transition from cold-based to warm-based ice (Figs.2 and 4A). The gully features at Wolf Crags are similar to those identified by Chandler and Lukas (2017) at Ben More Coigach, northwest Scotland, which were also attributed to cold-based ice on the plateau. The presence of meltwater channels trending down valley and extending onto the summit surface in adjacent valleys, shown in Fig.7, is further evidence of erosional processes at the plateau edge representing a transition from cold-based non-erosive ice to temperate ice. It is believed that the draw-down of glacier ice from a plateau surface into an outlet glacier results in enhanced basal shear stress and strain heating consequently leading to sliding and erosion (Rea et al., 1998). Such erosional features are used as a landform record of deglaciation in areas of cold-based ice in southern Norway by Sollid and Sorbel (1994) and other glacier reconstructions in Britain (e.g. Livingstone et al., 2010; Evans et al., 2012).

The presence of blockfields on the summits surrounding the glacial valleys north of Helvellyn and south of Wolf Crags are suggestive of transitional zones between different thermal boundaries within the glacier (Fig.7), with similar features recorded by McDougall (2001) in the Central Fells of the Lake District. Blockfields are typical of contemporary plateau icefield glaciers where they are preserved in regions of cold-based ice on the summits (Rea et al., 1996). Boston et al. (2015), Brown (2009) and McDougall (2001; 2013) also identified blockfields on plateau summits and used this as an indicator of cold-based plateau ice in reconstructions in Britain. The preservation of the British Irish Ice Sheet drumlin identified by Livingstone et al. (2008) on the summit above Groove Beck is further evidence of a protective ice mass above Groove Beck and Wolf Crags. The reconstructed ice-marginal positions in Wolf Crags and Groove Beck (Fig. 8) also indicate confluence with a mutual ice source on the summit, this is similar to the pattern of glaciation, also associated with plateau icefields, in the Central Fells of the Lake District during the LLS (McDougall, 2001).

Comparison with Previous Reconstructions

Wolf Crags was one of the smaller cirque glaciers identified by Manley (1959) and Sissons (1980) and an unusually high southwest snowblow factor was calculated to nourish the glacier, as a result of the extensive plateau to the south. Sissons (1980) also commented that the size of the reconstructed glaciers in the northeast Lake District were much smaller than expected due to the favourable locations in terms of direct insolation leading to the conclusion of low snowfall over the region. By contrast, Sissons and Sutherland (1976) had predicted high amounts of precipitation, highlighting the discrepancies between the geomorphological work and palaeoclimate reconstructions. The geomorphological evidence presented here indicates that the Wolf Crags cirque-type feature identified by Sissons (1980) most likely formed in association with an outlet glacier. If this is correct, the complex and contradictory palaeoclimate interpretations made by Sissons and Sutherland (1976) and Sissons (1980), to support a localised cirque glacier, are unnecessary.

Conclusion

The geomorphological mapping performed at Wolf Crags and Groove Beck strongly suggest a plateau icefield existed on the summit above Wolf Crags during the LLS. The presence of recessional lateral moraines extending towards the plateau is indicative of outlet glaciers with ice origins on the summit. This is supported by preserved blockfields on the summits and lateral meltwater channels and gullies on the plateau edges, key indicators of cold-based ice on the plateau. This interpretation differs from the valley-and cirque-dominated alpine glacial reconstruction for the Lake District proposed by both Manley (1959) and Sissons (1980) and further supports the works of McDougall (2001, 2013) who reinterpreted the valley and cirque glaciers of the central Lake District as outlet glaciers of plateau icefields. We, therefore, believe the style of glaciation inferred from the works of Manley (1959) and Sissons (1980) should be re-assessed along with the local palaeoclimate evaluations.

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